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ECBC-TR-135

NBC FILTER PERFORMANCE

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October 2001

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20011206 057

Aberdeen Proving Ground, MD 21010-5424

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave Blank)		2. REPORT DATE 2001 October		3. REPORT TYPE AND DATES COVERED Final; 95 Aug - 98 Dec
4. TITLE AND SUBTITLE NBC Filter Performance			5. FUNDING NUMBERS NONE	
6. AUTHOR(S) Morrison, Robert W.				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) DIR, ECBC, ATTN: AMSSB-RRT-PF, APG, MD 21010-5424			8. PERFORMING ORGANIZATION REPORT NUMBER ECBC-TR-135	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words) This document summarizes the ability of nuclear, biological and chemical (NBC) filters to remove chemical/ biological aerosols and vapors. The NBC filtration systems consist of a particulate filter to remove liquid and solid phase toxic materials, and a vapor filter to remove gas phase toxic materials. The particulate filtration stage consists of HEPA media, which provides 99.97% filtration efficiency. The vapor filtration stage provides high capacity removal of all CW agents at efficiencies of >99.999% for the super-toxic nerve agents. This stage consists of activated carbon impregnated with materials that react with those agent vapors that are ineffectively adsorbed by the activated carbon. The NBC filters also provide protection against a wide range of toxic industrial materials (TIMs). These effectively filtered TIMs include those in aerosol/particulate form and vapors that exhibit either acid properties or possess a vapor pressure of less than about 10 mm Hg at the filter temperature. Particulate filtration performance of NBC filters is verified using a test aerosol of a 0.3 µm particle size. Vapor filtration performance is verified by determining the agent filtration of the adsorbent through "life" testing with a variety of performance-limiting agents, as well as filter "life" testing to verify acceptable efficiency and capacity.				
14. SUBJECT TERMS NBC filtration Toxic industrial materials ASZM-TEDA HEPA			15. NUMBER OF PAGES 14	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT UNCLASSIFIED	18. SECURITY CLASSIFICATION OF THIS PAGE UNCLASSIFIED	19. SECURITY CLASSIFICATION OF ABSTRACT UNCLASSIFIED	20. LIMITATION OF ABSTRACT UL	

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PREFACE

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NBC FILTER PERFORMANCE

1. INTRODUCTION

This document summarizes the ability of nuclear, biological and chemical (NBC) filters to remove chemical and/or biological aerosols and vapors. The NBC filtration technology has gradually evolved over the 80 years since the beginning of the modern era of chemical warfare (CW) in World War I. Over this time, the filtration performance of NBC filters has been extensively studied and technology improvements have been implemented on an incremental basis. From these studies and filter development work, a large database is available on the performance of NBC filters in removing (CW) agents. In addition, some effort has also been expended in characterizing NBC filter performance in removing toxic industrial materials (TIMs), but the database that exists describing TIM filtration contains many gaps. However, from the scientific principles that apply to the technologies used in NBC filters, one is able to confidently predict, in general qualitative terms, the effectiveness of NBC filters in providing filtration of many TIMs. Performance against some compounds is uncertain however, and recently work has been undertaken to close these TIM filtration data gaps.

The NBC filtration systems consist of a particulate filter to remove liquid and solid phase toxic materials, followed by a vapor filter to remove gas phase toxic materials. The particulate filtration stage consists of a high efficiency particulate air (HEPA) grade filter media. The vapor filtration stage consists of a bed of granular activated carbon that has been impregnated with reactive chemicals. The particulate filtration stage is typically located upstream of the vapor filtration stage so that volatile material released by the trapped aerosol is removed by the vapor filter. The M13 filter element pair used with the M17 protective mask is an exception to this orientation. This filter provides single-stage filtration through application of a composite material consisting of fine particle size impregnated activated carbon (for vapor filtration) mixed with glass and polymer fibers (for aerosol filtration). A disadvantage of this single-stage approach is that the aerosol can penetrate a significant distance into the composite aerosol/vapor filter material before being removed from the airstream. For these deeply penetrating aerosol droplets/particulates, the full adsorbent bed depth is not available for removal of any vapors that evolve from the filtered material (such as thickened nerve agent). Thus, the service life of the filter can be shorter than that from a filter consisting of an aerosol filtration media upstream of an equivalent adsorbent bed.

2. PARTICULATE FILTRATION

The particulate filter consists of HEPA media, which provides 99.97% filtration efficiency of 0.3 μm diameter aerosol particles (liquid and solid). The size of 0.3 μm is approximately the most penetrating particle through HEPA media. The HEPA media is a thin mat of very fine (0.5 to 10 μm in diameter) glass fibers mixed with high temperature resistant polymeric fibers that are included to increase strength. Typical chemical and biological (CB) aerosol dispersions in air are in the 1 to 10 μm range, and the HEPA media provides filtration

efficiency of better than 99.9999% in that particle size range. Particles smaller than approximately 0.3 μm are also removed with greater efficiency than 99.97%. The HEPA media is pleated to increase the area of the material used, thus decreasing the airflow velocity through the media. Low airflow velocity results in high filtration efficiency and low pressure drop. Because the flow is being directed over a larger area, the media can also filter much more aerosol mass without the airflow resistance increasing to an unacceptable level. Examples of chemicals removed by this aerosol filter stage include the tear gases and low volatility nerve agents such as VX. Biological agents, such as anthrax, and radioactive particulates are also efficiently removed by the HEPA media in NBC filters.

For the traditional HEPA media used in NBC filters, filtration efficiency tends to increase with loading of aerosol on the media. This increase occurs because the spaces between fibers are reduced in size by the accumulated aerosol. However, this accumulated aerosol has the unwanted effect of increased airflow resistance. Aerosol filter change-out is generally based on the airflow resistance rising to unacceptable levels. At the time of change-out, the filtration efficiency of an aerosol filter is typically higher than that provided when the filter was new.

The extent of aerosol loading resulting in the need for filter change-out varies greatly from one filter design to another. Factors contributing to the variability in aerosol capacity for different filter designs are as follows.

- The airflow velocity through the media (can be controlled by the extent of pleating).
- The margin that the airflow resistance of the filter when new is below the maximum allowable value. The nature of the aerosol material also affects airflow resistance and thus filter change-out interval. An equivalent mass of a smaller particle size aerosol collected by a filter results in more airflow resistance than does a larger particle size aerosol. Aerosols that are hygroscopic tend to result in greater airflow resistance because of clumping of the filter cake.

3. VAPOR FILTRATION

The vapor filter, which consists of activated carbon that has been impregnated with reactive materials, is immediately downstream of the aerosol filter. This impregnated, activated carbon filters vapors by two mechanisms, which are physical adsorption in the pores of the activated carbon and chemical reaction with the impregnants. Low vapor pressure chemicals such as the nerve [e.g., isopropyl methylphosphonofluoridate (GB)] and vesicants agents [e.g., bis-(2-chloroethyl) sulfide (HD)] are removed very effectively by physical adsorption alone in the microporous structure of the carbon. Relatively high vapor pressure agents, such as the blood agents cyanogen chloride (CK) and hydrogen cyanide (AC), are weakly physically adsorbed and will quickly penetrate a nonreactive activated carbon. Thus, specific reactive chemicals have been identified that chemically decompose those high vapor pressure agents. These reactive chemicals are impregnated on the activated carbon to provide effective filtration of the complete spectrum of CW agents.

For approximately 50 years in the United States, CW agent vapor filters contained the reactive adsorbent ASC carbon, which is a coal-based activated carbon impregnated with chemical compounds containing copper, silver, and chromium. Recently, the ASC carbon was determined to be a hazardous waste under the Resource Conservation and Recovery Act (RCRA). Because of high costs of disposing of spent ASC carbon filters, the ASZM-TEDA carbon (a chromium-free carbon) was developed and has been adopted in nearly all United States NBC filters produced since 1993. This ASZM-TEDA carbon is a coal-based activated carbon impregnated with copper, zinc, silver, and molybdenum compounds, as well as with triethylenediamine (TEDA). The ASC carbon and ASZM-TEDA carbon use a special subgrade of BPL activated carbon. The Calgon Carbon Corporation (Pittsburgh, PA) as the substrate for the impregnants. The protection provided by these two sorbents against CW agents is nearly equivalent.

The NBC filters containing ASC or ASZM-TEDA carbon provide a high level of protection against all CW agent vapors listed in FM 3-9 entitled, "Potential Military Chemical/Biological Agents and Compounds." With few exceptions, the following minimum levels of filtration performance are provided by NBC filters at their rated flow.

Agent Class	Example Agent	Filtration Performance, Ct (mg-min/m ³)
Nerve	Isopropyl methylphosphonofluoridate (GB)	300,000
Vesicant	Bis-(2-chloroethyl) sulfide (HD)	300,000
Blood	Cyanogen chloride (CK)	80,000
Choking	Carbonyl chloride or phosgene (CG)	120,000

The Ct is the challenge concentration to the filter integrated with respect to the time over which the challenge occurred. Thus, an example of a scenario that would result in a filter performance Ct of 300,000 mg-min/m³ would be a GB challenge concentration of 100 mg/m³ for 3,000 min.

The ASC carbon and ASZM-TEDA carbon were developed specifically to filter CW agent vapors. However, the sorbents are also effective in filtering a wide variety of industrial chemical vapors. The vapor filtration performance of these sorbents depends primarily on the vapor pressure and the reaction chemistry of the chemical. Chemicals with low vapor pressures are effectively filtered by physical adsorption alone. As a general rule of thumb, chemicals with a vapor pressure below about 10 mm Hg at the temperature of the filter would be very effectively removed by physical adsorption in pores of the activated carbon. As one considers higher and higher vapor pressure chemicals, the ability of the sorbent to remove the chemical vapor by physical adsorption decreases. For these higher vapor pressure chemicals, reaction with the impregnants is necessary for effective filtration performance.

As a first level screen to estimate the effectiveness of ASC carbon or ASZM-TEDA carbon in filtering a specific vapor, one considers the vapor pressure of the chemical. If the vapor pressure is such that physical adsorption does not appear to be adequate to filter the

chemical, reaction with the impregnants (or perhaps the carbon surface itself) could be a removal mechanism. By considering the chemical reaction characteristics of the chemical and the impregnants, an assessment can often establish the potential for removal of a chemical vapor by reaction with the impregnants. However, risk exists in basing a determination of filtration performance on expected reactivity. Reactivity, which is known to exist between two chemicals in a laboratory flask, may not be manifested to the same extent on the surface of activated carbon.

Of course, the most definitive determination of the ability of a filter to remove a chemical is to perform experimentation in the form of a chemical challenge of the filter in question (frequently called a filter life test). Nearly equivalent data can be obtained by performing a challenge test of a bed of the adsorbent used in the filter in question. This challenge test of the adsorbent bed must be performed at the same bed depth and airflow velocity as for the filter.

Even for chemicals that are removed very effectively by NBC filters, the amount of chemical that can be removed by the filter is limited by the space available for physical adsorption in the pore structure of the adsorbent and the amount of reactive impregnant contained on the adsorbent. In general, if continued long enough, breakthrough will eventually occur for every chemical vapor challenge to a filter. An exception to this statement would be for a purely catalytic reaction. However, such mechanisms for filters operated at typical ambient temperatures are rare. The rate that the filter capacity is depleted is dependent on the concentration of challenge to the filter and the flow rate into the filter. Higher challenge concentrations and higher flow rates (such as heavier breathing rates for mask filters) result in shorter breakthrough times.

4. SPECIFIC NBC FILTER PERFORMANCE INFORMATION

The NBC filters provide effective filtration against a broad spectrum of chemicals but certainly not all chemicals. The chemicals described in this paragraph are effectively filtered by NBC filters at a challenge level of at least 40,000 mg-min/m³ (equivalent to a challenge concentration of 1,000 mg/m³ for 40 min). The filtration efficiency for chemical vapors is at least 99.999%. This protection level is provided at all ambient temperatures and humidities except when near 100% relative humidity (RH) conditions exist. **THE FILTER MUST BE FREE OF LIQUID WATER.** The NBC filters provide good protection (per criteria above) against the following chemicals.

- All CB Warfare Agents. All CB warfare agents listed in FM 3-9 (also known as NAVFAC P-467 and AFR 355-7).

- All Aerosols. Aerosol filtration efficiency is at least 99.97%, generally >99.9999% for typical threat aerosol sizes. The end of service life of the aerosol filter is indicated by the airflow resistance rising to unacceptable levels.

- Organic Chemicals. Organic chemicals with vapor pressures of less than about 10 mm Hg at the temperature of the filter. However, consideration must also be given to the potential for reactivity of the chemical vapor with the reactive impregnants on the carbon adsorbent in the filter or with the carbon surface itself. Toxic breakdown products could be produced should a reaction occur. If these toxic breakdown products are not effectively removed by the adsorbent, they could pose a hazard to the user of the filter.

- Acid Gases.

- Hydrogen Chloride
- Hydrogen Fluoride
- Hydrogen Bromide
- Fluorine
- Chlorine
- Hydrogen Sulfide
- Sulfur Dioxide
- Sulfuric Acid

Limited protection is provided against chemicals with vapor pressures between about 10 and 100 mm Hg at the temperature of the filter. However, filtration performance may be poor at high relative humidity. Also, although protection against chemicals falling within this vapor pressure range may be adequate for a period of time, the retention of the chemical by the filter is likely to be inadequate. On continued use of the filter, the chemical is likely to off-gas into the product air exiting the filter. The NBC filters should not be relied on to provide a high level of protection against chemicals with vapor pressures falling in the 10 and 100 mm Hg range. However, the NBC filters may be useful against brief, low concentration challenges. If exposed to toxic chemicals falling in this vapor pressure range, the filter should be replaced immediately after the chemical exposure ends.

The NBC filters will not provide significant protection against many chemicals with vapor pressures greater than about 100 mm Hg. Exceptions would be those chemicals that react with the impregnants or the carbon surface to produce reaction products that are either nonhazardous or are retained by the adsorbent. (There is little information available regarding many of these reactive chemicals). NBC filters will NOT provide protection against the following common industrial chemicals.

- Carbon Monoxide
- Carbon Dioxide
- Nitric Oxide
- Nitrogen Dioxide
- Ammonia
- Metal Carbonyls

The NBC filters do allow rapid penetration of all normal atmospheric gases including nitrogen, oxygen, water vapor, and argon.

5. FILTER PERFORMANCE ASSESSMENT

5.1 Aerosol Filtration.

Typically, the filtration efficiency of an aerosol filter is measured by using a 0.3 μm monodisperse aerosol of either dioctylphthalate (DOP) or a polyalphaolefin known as Emery 3004 (also known as Ethylflow 164 or Durasyn 164). The filtration efficiency of the HEPA media used in NBC filtration is nearly independent of the physical state (liquid or solid) of either the aerosol or the properties of the aerosol other than particle size. Thus, the results of the DOP or Emery 3004 test are representative of the performance of the aerosol filter in removing CB agents. Filter testing with actual CB aerosols is rarely performed. Aerosol filtration efficiency testing is conducted during filter development and for production acceptance verification. In addition to efficiency testing, the extent that airflow resistance increases with loading is generally addressed during filter development, using standard commercial test methods with materials such as "road dust."

5.2 Vapor Filtration.

The approach to verify adequacy of vapor filtration is to inspect adsorbent performance through "gas life" tests with a variety of agents and to quantify filter performance with design limiting agents/simulants. For production lot acceptance of filters, testing includes only two design limiting agents/simulants. However, during filter development, additional agent testing is generally conducted to verify the filter design's effectiveness. Before any production lot of filters is built, the Government verifies that the adsorbent production lot to be used in that filter production lot possesses the required level of agent filtration performance. As a result of this adsorbent testing, the ASZM-TEDA Carbon production lot to be used in the specific filter production lot is known to possess adequate agent sorption performance. Because it is economically impractical to test the adsorbent with every chemical warfare agent, only four difficult-to-remove agents have been selected to verify the adequacy of filtration performance of adsorbent production lots. The test agents/simulants used to verify adsorbent performance are cyanogen chloride, hydrogen cyanide, phosgene (carbonyl chloride) and dimethyl methylphosphonate (DMMP) as a simulant for GB. By way of its simulant DMMP, GB is used to verify adsorbent performance because it is the most weakly adsorbed of the physically adsorbed agents. Phosgene was selected to assess acid gas removal capability of the adsorbent because many agents possess acidic characteristics, either inherently or through hydrolysis of the agent. The two cyanide containing agents (cyanogen chloride and hydrogen cyanide) are used in adsorbent performance verification because of their relatively low capacity with the impregnant formulation of ASZM-TEDA Carbon. Thus, these two cyanide agents are important performance limiters for ASZM-TEDA Carbon. If a different adsorbent were used in NBC filters, a different set of design limiting agents may be required to adequately assess adsorbent performance.

Because the agent filtration performance of every adsorbent production lot is verified prior to its use, production lot filters need not be tested to verify filtration performance for the broad range of CW agents. However, the filter lot needs to be inspected to ensure that a sufficient quantity of adsorbent has been used, the adsorbent bed has been adequately packed, and the reactivity of the impregnants on the adsorbent have not been compromised during filter production.

Verification of adequacy of the adsorbent fill quantity and packing is typically obtained through filter "protection life" testing using the nerve agent simulant DMMP (dimethyl methylphosphonate) augmented with some GB testing during filter development. Protection life testing is conducted by challenging the filter with a constant concentration of the chemical vapor in an airstream flowing at the rated flow of the filter under test. In some cases, humidity is added to the airstream. The agent GB is used because it is the filtration performance limiting agent representing all nerve agents and vesicants. Of those agents for which physical adsorption is the primary removal mechanism, GB has the highest vapor pressure. Physical adsorption by activated carbon, such as that used in NBC filters, is basically a phase change process in which the vapor pressure of the agent plays an important role. Ignoring for the moment the role that the reactive impregnants on the adsorbent play, the ability of a filter containing activated carbon to remove a specific chemical generally varies inversely with the vapor pressure of that chemical. Thus, GB is the most "weakly adsorbed" of those agents that are filtered effectively by physical adsorption alone. The agent GB is therefore used as a basis to insure that military filters provide adequate protection against all known nerve agents and vesicants. In other words, if an NBC filter has the ability to remove agent GB to a certain extent, that filter will remove all other nerve agents and vesicants to an equivalent or greater extent. The simulant DMMP has been shown to effectively characterize the GB filtration performance of NBC filters and is frequently used as a substitute for GB to save money and eliminate the toxicity hazard associated with agents.

Verification that the carbon impregnants have not been compromised during filter production is performed using cyanogen chloride (CK). CK has been selected for this role because, as mentioned above, it is one of the most difficult to filter agents for which chemical reaction is required for their effective removal. In addition, CK removal is affected to the greatest extent of all agents by the effects of adsorbent "aging" resulting from exposure to high temperature and relative humidity. Generally, if an NBC filter can provide adequate CK protection, that filter generally will provide adequate filtration for all other agents for which chemical reaction is necessary for effective removal. During development of a new filtration system, a number of the "full-up" filters are tested for CK filtration performance. In addition, production lot acceptance testing is conducted with CK for filters with rated flows of 12 cfm or less. However, because high costs associated with conducting high flow testing with a toxic compound production lot acceptance, CK testing of filters with rated flows greater than 12 cfm is not performed. Instead, samples of carbon from the filter production line are CK tested in small tubes in a laboratory. These carbon samples have been exposed to same environment as the carbon filling the filters on the production line, thereby, assurance is obtained that the reactivity of the carbon has not been compromised by the filter production processes used by the manufacturer.

6. CONCLUSIONS

Nuclear, biological, and chemical (NBC) filters provide a high level of protection against all chemical and biological warfare agents. The current filtration technologies used in NBC filters are a pleated high efficiency particulate air (HEPA) grade fibrous mat for aerosol filtration and activated carbon impregnated with reactive chemicals for vapor filtration. The NBC filters provide at least 99.97% filtration efficiency for submicron size particulates and at least 99.9999% filtration efficiency for particulates of micron size or greater.

The carbonaceous adsorbent used in NBC filters removes the vapors of low vapor pressure chemicals by physical adsorption in micropores; whereas, the vapors of higher vapor pressure chemicals are removed by chemical reaction with impregnants applied to the surface of the activated carbon. The NBC filters provide effective filtration against many toxic industrial materials, but some weaknesses do exist.

Adequacy of aerosol filtration performance is verified using a 0.3 μm aerosol of dioctylphthalate or a polyalphaolefin known as Emery 3004. Adequacy of vapor filtration is verified by means of extensive agent testing of the adsorbent, and by isopropyl methylphosphonofluoridate/dimethyl methylphosphonate and cyanogen chloride protection life testing of the full-up filter.